

Six New Recycled Globular Cluster Pulsars Discovered with the Green Bank Telescope

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ABSTRACT

We have completed sensitive searches for new pulsars in seven globular clusters using the Robert C. Byrd Green Bank Telescope, and have discovered six new recycled pulsars (four in NGC 6517 and two in M22), five of which are fully recycled millisecond pulsars with $P < 10$ ms. We report full timing solutions for all six new pulsars and provide estimates of their flux densities and spectral indices. None of the pulsars are detected in archival Chandra data down to $L_X \sim 10^{32}$ erg s⁻¹ for NGC 6517 and $L_X \sim 10^{31}$ erg s⁻¹ for M22. One of the millisecond pulsars in M22 appears to have a very low mass companion, and is likely a new “black widow”. A second binary pulsar in NGC 6517 is in a long-period, mildly eccentric orbit. We are able to set some lower limits on the age of the system, and find that it may be less than a few hundred million years old, which would indicate recent pulsar recycling in NGC 6517. An isolated pulsar in NGC 6517 that lies about 20 core radii from the cluster center appears to have been ejected from the core by interacting with a massive binary. By analyzing the luminosity function of the pulsars in NGC 6517, we predict the cluster to harbor roughly a dozen pulsars. We use the observed period derivatives of three pulsars to set lower limits on the mass-to-light ratios in the cores of their host clusters, and find no evidence for large amounts of low-luminosity matter. We also discuss reasons for non-detections in some of the clusters we searched.

Subject headings: pulsars: individual (J1836-2354A, J1836-2354B, J1801-0857A, J1801-0857B, J1801-0857C, J1801-0857D) — globular clusters: individual (M22, NGC 6517)

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1. Introduction

The first globular cluster (GC) pulsar was discovered by Lyne et al. (1987). Since then, 143 pulsars have been discovered in 27 GCs⁵, the vast majority of which are millisecond pulsars (MSPs). In fact, over half of all known MSPs are in clusters, which has been attributed to frequent dynamical interactions that create mass-transferring binaries that are capable of forming recycled pulsars (Camilo & Rasio 2005), as well as to very deep, targeted surveys. These same dynamical encounters give rise to systems that are seen only rarely, if at all, in the Galaxy, such as the fastest spinning MSP (Hessels et al. 2006), highly eccentric binaries (Ransom et al. 2005; Freire et al. 2007), massive neutron stars (Freire et al. 2008), pulsar-main sequence binaries (D’Amico et al. 2001), and many “black widow” systems (King et al. 2005). After a burst of activity in the early 1990s, the pace of discovery of GC pulsars slowed until about 2000, after which improvements in sensitivity and computing power led to an explosion of new pulsars. The Robert C. Byrd Green Bank Telescope (GBT), completed in 2001, has been especially important, having discovered 70 GC pulsars. Despite this, most searches of GCs are still sensitivity limited (Ransom 2008), meaning that we have only begun to scratch the surface of this exciting population.

Pooley et al. (2003) have shown that a good predictor of the number of low mass X-ray binaries (LMXBs) in GCs is the two-body core interaction rate, $\Gamma_c \propto \rho_0^{1.5} r_c^2$, where ρ_0 is the central density and r_c is the core radius. As LMXBs are the progenitors to MSPs, one may expect that Γ_c would also be a good predictor of the number of cluster pulsars, and this is indeed observed, especially when scaled by the distance D of the GC to account for flux losses (i.e., Γ_c/D^2). This parameter was used to select twelve promising clusters for GBT surveys in 2004–2005. Results of these surveys include the rich GCs Terzan 5 (Ransom et al. 2005), M28 (Bégin et al., in prep.), NGC 6440, and NGC 6441 (Freire et al. 2008), all of which have been shown to contain many pulsars.

Here we report on searches of an additional seven GCs that have resulted in the discovery of six new pulsars. In §2 we describe the sample of clusters that were targeted and the parameters of our searches. Follow-up timing observations of the newly discovered pulsars are described in §3 with specific results presented in §4. We summarize our results in §5.

⁵For an up-to-date list see <http://www.naic.edu/~pfreire/GCpsr.html>

2. Search Parameters

Data were collected with the GBT at a central frequency of 2 GHz using 800 MHz of instantaneous bandwidth, although persistent radio frequency interference (RFI) reduced the usable bandwidth to 600 MHz. The Pulsar Spigot back-end (Kaplan et al. 2005) was used in a mode that offered 1024 frequency channels over 800 MHz of bandwidth and a sampling time of $80.96 \mu\text{s}$. Total system temperatures were typically 24–30 K. The contribution from the Galactic background was estimated by scaling the values from Haslam et al. (1982) to 2 GHz assuming a spectral index of -2.6 , and was usually $T_{\text{Gal}} \lesssim 2$ K (though Liller 1 and Terzan 6, being closer to the Galactic plane, suffered from T_{Gal} of 7 and 5 K, respectively). Integration times and approximate limiting flux densities can be found in Table 1, along with some other properties of each cluster.

Liller 1 was also searched in 2007, taking advantage of a new, 2048 frequency channel Spigot mode. Liller 1 is an intriguing cluster because despite a very high central density and the presence of unresolved, steep spectrum radio emission in its core (Fruchter & Goss 2000), no pulsars have been detected. The likely culprit is dispersive smearing and scatter broadening of pulsar signals caused by free electrons along the line of sight, thanks to its location very near the bulge of the Galaxy (Liller 1 is predicted to have a dispersion measure, $\text{DM} \sim 740 \text{ pc cm}^{-3}$). The improved frequency resolution of the new Spigot mode offered a factor of two improvement in dispersive smearing compared to previous searches at 2 GHz. We also observed Liller 1 at a frequency of 4.8 GHz, hoping to overcome scattering (which roughly scales as f^{-4}), while retaining sensitivity to any bright pulsars (pulsars are steep spectrum sources and thus dimmer at high frequency).

All searches were processed using the PRESTO software suite (Ransom et al. 2002). After removing RFI, the data were transformed to the Solar System barycenter, and de-dispersed time series were created at a range of trial DMs that were based upon the NE2001 model of free electron density (Cordes & Lazio 2002). Because of uncertainties in this model, and drawing on past experience with similar pulsar searches, we used a minimum DM of 10 pc cm^{-3} and maximum DM 1.5 times greater than that predicted by NE2001. Acceleration searches for isolated and binary pulsars were carried out in the Fourier domain for signals with maximum accelerations of $z_{\text{max}} = \pm 400\text{--}800$ Fourier bins. This corresponds to a physical acceleration of

$$a_{\text{max}} = \frac{z_{\text{max}} c P}{t_{\text{obs}}^2} \quad (1)$$

where c is the speed of light, P is the spin period of the pulsar, and t_{obs} is the length of the data that was searched. We searched the full length observations to maximize our sensitivity to weak pulsars, and also broke the observations into 10 and 30 minute chunks to increase

sensitivity to bright pulsars in tight binaries. Exact values of a_{\max} for full length searches for a 3 ms pulsar can be found in Table 1. We also carried out single-pulse searches to look for transient emission. Final candidates were visually inspected and grouped into potential pulsars, RFI, or random noise. In many cases a GC was observed twice, in which case we were quickly able to confirm or reject marginal candidates.

3. Pulsar Timing Analysis

Six new pulsars were discovered—four in NGC 6517 and two in M22. Timing observations for the pulsars in M22 began in 2008 August, and follow-up of the NGC 6517 pulsars (which were discovered shortly after those in M22) commenced in 2008 October. Initial observations continued to use the Spigot in the 2048 channel mode described in §2, but we switched to the new Green Bank Ultimate Pulsar Processing Instrument (GUPPI) (DuPlain et al. 2008) back-end in 2008 October. GUPPI offers more dynamic range, improved RFI resistance, and better sampling time (40.96–64 μ s) than the Spigot. While most of our timing was done at 2 GHz, we obtained two 1.4 GHz observations of M22 and one of NGC 6517. High signal-to-noise average pulse profiles were obtained by summing all detections for a pulsar (see Figure 1). We created standard pulse profiles by fitting one or more Gaussians to the average pulse profiles. Standard profiles were used to compute pulse times of arrival (TOAs) using **PRESTO** or **PSRCHIVE** (Hotan et al. 2004) depending on data format. One TOA was obtained per observation for isolated pulsars, while multiple TOAs (~ 6) were obtained for binary pulsars to provide good sampling of the orbit. Phase connected timing solutions were obtained using the **TEMPO**⁶ software package and the DE405 Solar System ephemeris. Timing solutions for all pulsars except J1801–0857C and J1801–0857D (hereafter NGC 6517C and D) could be reliably phase connected to the 2005 discovery observations, providing a 1574 and 1465 day baseline for the pulsars in M22 and NGC 6517, respectively. For NGC 6517C and D, phase connected solutions include data spanning 463 days. In most cases, the reduced χ^2 returned by **TEMPO** was greater than one. Since we observe no unmodeled systematics in our fits, this is most likely attributable to under-estimated errors on individual TOAs. We multiplied our TOA errors by a constant factor to obtain a reduced $\chi^2 = 1$. Post-fit residuals can be found in Fig. 2.

⁶<http://tempo.sourceforge.net>

4. Results

Three of the four new pulsars in NGC 6517 are isolated MSPs (J1801–0857A, hereafter NGC 6517A, NGC 6517C, and NGC 6517D). J1801–0857B (NGC 6517B) is a partially recycled binary pulsar. M22 contains one binary MSP (J1836–2354A; M22A) and one isolated MSP (J1836–2354B; M22B). The full timing solutions are given in Tables 2 and 3, along with the offsets from the cores of the clusters, the 2 and 1.4 GHz mean flux densities, and the spectral indices (α) implied by from these flux densities. The coordinates of the optical centers of NGC 6517 and M22 were taken from Shaul & White (1986) and Goldsbury et al. (2010), respectively. Rough flux density measurements were made by assuming that the off-pulse RMS noise level was described by the radiometer equation,

$$\sigma = \frac{T_{\text{tot}}}{G\sqrt{n_{\text{pol}}\Delta f t_{\text{obs}}}} \quad (2)$$

where T_{tot} is the total system temperature, G is the telescope gain, $n_{\text{pol}} = 2$ is the number of summed polarizations, and Δf is the bandwidth. We estimate a 10%–20% fractional uncertainty in these measurements, which corresponds to an uncertainty $\alpha \pm 1.1$. NGC 6517D was not detected at 1.4 GHz, so no information on the spectral index is available.

Archival Chandra data exists for both clusters, but upon visual inspection we find no sources coincident with the positions for the pulsars obtained in our timing analysis. NGC 6517 was observed for ~ 24 ks with ACIS-S in 2009 (Obs. ID 9597). For a neutral hydrogen column density $N_{\text{H}} = 3 \times 10^{21} \text{ cm}^{-2}$ and $D = 10.6$ kpc, and assuming a limiting count rate of 10 counts, we estimate an unabsorbed luminosity limit $L_{\text{X}} \sim 10^{32} \text{ erg s}^{-1}$ in the 0.3–8 keV band for these observations. This limit applies to both a 0.2 keV black body or a source with a power law spectrum and photon index of 1.3. M22 was observed for ~ 16 ks with ACIS-S in 2005 (Obs. ID 5437). For $N_{\text{H}} = 1.6 \times 10^{21} \text{ cm}^{-2}$ and $D = 3.2$ kpc, we estimate $L_{\text{X}} \sim 10^{31} \text{ erg s}^{-1}$. These luminosity limits lie above the typical $L_{\text{X}} \sim 10^{30} \text{ erg s}^{-1}$ for the MSPs in 47 Tucanae (Bogdanov et al. 2006) and M28 (Bogdanov et al. 2011), so it is likely that any X-ray emission from the pulsars in NGC 6517 or M22 is simply too faint to be visible given the most recent observations.

⁷To calculate N_{H} we used the **Colden** tool provided online at <http://cxc.harvard.edu/toolkit/colden.jsp>

4.1. NGC 6517B

The orbital period of NGC 6517B is ~ 59 days, the fifth longest of any known GC pulsar. The orbit is mildly eccentric ($e = 0.03$), a trait seen in four other GC pulsars with $P_b > 30$ days. Any eccentricity gained during the formation of the binary is expected to dissipate quickly, so the observed eccentricity is likely due to gravitational perturbations of passing stars. Following Rasio & Heggie (1995) we estimate the time required to induce this eccentricity,

$$t_{>e} \simeq 4 \times 10^{11} \text{ yr} \left(\frac{n}{10^4 \text{ pc}^{-3}} \right)^{-1} \left(\frac{v}{10 \text{ km s}^{-1}} \right) \left(\frac{P_b}{\text{days}} \right)^{-2/3} e^{2/5} \quad (3)$$

where n is the number density of stars in the neighborhood of the pulsar, v is the one-dimensional core velocity dispersion, and P_b is the binary period. We were unable to find a measured central velocity dispersion for NGC 6517 in the literature, but O. Y. Gnedin reports⁸ $v = 20.6 \text{ km s}^{-1}$ based on photometric models for a mass-to-light ratio $\Upsilon_V = 3 \text{ M}_\odot/\text{L}_{\odot,V}$ (note that this Υ_V is consistent with constraints we present in §4.4). We estimate n using the luminosity density reported in Harris (2010), $\Upsilon_V = 3$ for consistency, and an average stellar mass of 1 M_\odot , which yields $n \approx 4.7 \times 10^5 \text{ pc}^{-3}$. This average mass is higher than the typical 0.8 M_\odot turn-off mass in GCs, but is reasonable in the cluster core, where mass segregation will have caused heavy compact objects (stellar mass black holes, neutron stars, and massive white dwarfs) to sink towards the center; this raises the average mass in the neighborhood of NGC 6517B. Using these values $t_{>e} \sim 300 \text{ Myr}$. This limit is directly proportional to the assumed average stellar mass, so using a lower mass will provide a correspondingly lower limit.

We can also place a lower limit on the characteristic age of the pulsar by subtracting the effects of acceleration in the Galactic and cluster gravitational potential from the observed period derivative. The Galactic term is calculated under the approximation of a spherically symmetric Galaxy with a flat rotation curve (Phinney 1993) and is

$$\dot{P}_{\text{Gal}} = -7 \times 10^{-19} \left(\frac{P}{\text{s}} \right) \left(\cos b \cos \ell + \frac{\delta - \cos b \cos \ell}{1 + \delta^2 - 2\delta \cos b \cos \ell} \right) \quad (4)$$

where b and ℓ are the Galactic latitude and longitude of the cluster, $\delta = R_0/D$ and R_0 is the Sun's Galactocentric distance. Phinney (1993) showed that, to within $\sim 10\%$ accuracy for pulsars lying less than two core radii from the cluster center, the *maximum* contribution

⁸<http://www.astro.lsa.umich.edu/~ognedin/gc/vesc.dat>

to \dot{P} from the cluster is

$$\dot{P}_{\text{cluster,max}} = 5 \times 10^{-12} \left(\frac{P}{\text{s}} \right) \left(\frac{v}{\text{km s}^{-1}} \right)^2 \left[\left(\frac{R_c}{\text{km}} \right)^2 + \left(\frac{R_{\text{psr}}}{\text{km}} \right)^2 \right]^{1/2} \quad (5)$$

where R_c is the core radius and R_{psr} is the pulsar’s distance from the cluster center. We thus find a limit on the intrinsic spin down of $1.3 \times 10^{-17} \text{ s s}^{-1}$, which corresponds to $\tau_c \gtrsim 35 \text{ Myr}$. This is an order of magnitude smaller than our estimate of $t_{>e}$, so the true value of τ_c is probably higher. Although we can only set lower limits on $t_{>e}$ and τ_c , they are only a few percent the age of the cluster, and much lower than the characteristic ages of most other GC pulsars. This raises the possibility that NGC 6517B is young and that MSP formation has occurred in the cluster within the last few hundred million years.

4.2. NGC 6517D

NGC 6517D lies $71''$ from the cluster center, just over 20 core radii, making it the fourth most offset GC pulsar when scaled by the core radius (r_c). One may question if this pulsar is truly bound to the cluster or is just a chance alignment. However, there are two strong arguments for NGC 6517D actually being bound to the cluster. First, the pulsar is still just over one arcminute from the cluster center, and only about one third of the tidal radius. Second, the DM of the pulsar is consistent with that of the other three pulsars in NGC 6517 given the known distribution of DMs for other bulge clusters (Freire et al. 2005), despite being $\sim 8 \text{ pc cm}^{-3}$ lower than the average of the other three MSPs. These lines of reasoning, when taken together, lead us to believe that NGC 6517D is likely related to the cluster.

In that case, it is interesting to consider the probability of finding any pulsar at such a large projected offset from the cluster center. We begin with the assumption that the number density of pulsars as a function of the true distance from the center is $n_p(r) \propto (r^2 + r_c^2)^{-\alpha/2}$ (Phinney 1993). If the pulsars are in thermal equilibrium with the rest of the cluster stars, then $n_p \propto n_d^q$ where n_d is the number density of the dominant stars in the cluster, and q is the mass ratio of pulsars to these stars. We do not observe the true distance of the pulsar from the cluster center, but rather the projected offset, y . Hence, the relevant distribution is that for the surface density, $\sigma_p(y) \propto (y^2 + r_c^2)^{-(\alpha-1)/2}$. The number of pulsars that will lie further out than some observed offset, b , is

$$\frac{\int_b^{r_t} \sigma_p(y) y dy}{\int_0^{r_t} \sigma_p(y) y dy} \quad (6)$$

where r_t is the tidal radius of the cluster, which we take to be the “edge” of the cluster. NGC 6517D lies $20.7r_c$ from the cluster center, and $r_t = 68.3r_c$. For $q = 3$ (i.e., the dominant

stellar mass is $\sim 0.5 M_{\odot}$) we find that only 0.01% of pulsars should be found at the distance of NGC 6517D or further. For $q = 2$ (i.e., turn-off mass stars dominate), this number is 3.4%.

In the $q = 3$ case, it seems that NGC 6517D is indeed anomalous unless the cluster contains $\sim 10^4$ pulsars. A more likely possibility is that NGC 6517D is not in thermal equilibrium with the rest of the stars in the cluster, as is assumed in the above analysis. This can easily be explained if the pulsar was ejected from the cluster core in a dynamical event. The most likely scenario is that the pulsar was involved in a collision with a binary (which the pulsar may have been a member of) containing a more massive star. Any main sequence stars more massive than the pulsar would have died before the progenitor of NGC 6517D, so it must have been either a massive neutron star or a black hole. Similar scenarios have been invoked by Phinney & Sigurdsson (1991) to explain PSR B2127+11C in M15, and by Colpi et al. (2002) for PSR J1911-5958A in NGC 6752.

4.3. M22A

M22A is the second binary pulsar in our sample and lies in a nearly circular orbit with $P_b = 0.2$ days. We were unable to measure significant orbital eccentricity, but have obtained upper limits using two methods. First, we have used the ELL1 binary timing model in **TEMPO**, which was designed to fit low-eccentricity orbits. This model parameterizes the eccentricity and longitude of periastron as $\epsilon_1 = e \sin \omega$ and $\epsilon_2 = e \cos \omega$. We used the 5σ **TEMPO** errors to compute a conservative upper limit on the eccentricity, $e < 2.8 \times 10^{-4}$. We also follow Phinney (1992), computing $e_{\text{lim}} = \delta t (a \sin i / c)^{-1}$ where δt is our timing precision, and find $e < 1.6 \times 10^{-4}$, consistent with the first analysis.

The minimum mass of the companion to M22A was calculated assuming $M_{\text{psr}} = 1.4 M_{\odot}$ and $i = 90^\circ$ and is $M_{\text{c,min}} = 0.017 M_{\odot}$, or 18 Jupiter masses, while the median mass corresponding to $i = 60^\circ$ is only ~ 21 Jupiter masses. The presence of a low-mass companion in a tight orbit makes M22A a potential new “black widow” pulsar, where the pulsar is ablating its companion (King et al. 2005). Many black widow pulsars frequently eclipse due to plasma that has been stripped from the companion. We see no evidence for eclipses in M22A, but we believe this is probably due to a low inclination angle so that our line of sight never intersects any gas. The location of M22A on the $M_{\text{c,min}}$ vs. P_{orb} plane is similar to that of other non-eclipsing black widow pulsars (see King et al. 2005, Fig. 1). We are therefore confident in classifying M22A as a black widow.

M22A is the only pulsar we have found that is bright enough for useful polarimetry

measurements. However, we could not measure any reliable rotation measure from our 2 GHz observations, despite searching from $\pm 5000 \text{ rad m}^{-2}$, and see no evidence for polarized emission.

4.4. Cluster Mass-to-Light Ratios

The observed period derivative (\dot{P}) of GC pulsars is usually heavily contaminated by gravitational acceleration within the cluster potential (Phinney 1993). This makes cluster pulsars excellent probes of the cluster potential, and hence the enclosed mass at the projected position of the pulsars. Three of our newly discovered pulsars have $\dot{P} < 0$ which, if intrinsic to the pulsars, would imply that the pulsars are spinning *up*. This provides unambiguous evidence that these pulsars lie on the far side of their host cluster and are accelerating towards the Earth, and that the observed \dot{P} s are dominated by the cluster potential. This in turn can be used to provide a lower limit on the surface mass density within a *cylinder* running through the cluster (since the true position of the pulsar along the line-of-sight is unknown). When combined with the observed luminosity density, this provides a limit on the mass-to-light ratio, Υ . Following D’Amico et al. (2002),

$$\Upsilon_V \geq 1.96 \times 10^{17} \dot{P}_{\text{cluster}} \left(\frac{P}{\text{s}} \right)^{-1} \left(\frac{\Sigma_V(< \theta_\perp)}{10^4 \text{ L}_{\odot, V} \text{ pc}^{-2}} \right)^{-1} \quad (7)$$

where \dot{P}_{cluster} signifies the contribution to \dot{P}_{obs} by gravitational acceleration in the cluster, and $\Sigma_V(< \theta_\perp)$ is the mean surface brightness interior the position of the pulsar. To calculate $\Sigma_V(< \theta_\perp)$, we assume a constant surface brightness (taken from Harris (2010)) in the core of the cluster (all the pulsars that we analyze here are within the core radius of the cluster center). To arrive at \dot{P}_{cluster} , we must correct for other contributions to the observed \dot{P} , namely

$$\dot{P}_{\text{cluster}} = \dot{P}_{\text{obs}} - \dot{P}_{\text{int}} - \dot{P}_{\text{Gal}} - \dot{P}_{\text{pm}} \quad (8)$$

where \dot{P}_{int} is the intrinsic spin down of the pulsar and \dot{P}_{Gal} and \dot{P}_{pm} are the contributions from the potential of the Galaxy and proper motion, respectively. Since \dot{P}_{int} is unknown, we estimate it by assuming a characteristic age of 10 Gyr. That is,

$$\begin{aligned} \dot{P}_{\text{int}} &\approx \frac{P}{2\tau_c} \\ &\approx 1.6 \times 10^{-18} \text{ s}^{-1} P. \end{aligned} \quad (9)$$

The Galactic contribution was calculated as described in §4.1. The contribution from the proper motion of the cluster is simply $\dot{P}_{\text{pm}} = P\mu^2 D/c$ (Shklovskii 1970).

The results of the above analysis for NGC 6517A, NGC 6517D, and M22B are presented in Table 4. We were unable to find a proper motion for NGC 6517 in the literature, but we do not expect this to drastically change our conclusions. For example, at the distance of NGC 6517, a transverse velocity of $\sim 200 \text{ km s}^{-1}$ changes our constraint on Υ_V by $< 5\%$. The results for NGC 6517 are also particularly robust to changes in \dot{P}_{int} . In fact, if we make no corrections for \dot{P}_{int} at all, Υ_V changes by only $\sim 1\%$ for both NGC 6517A and C. However, since M22B has a small \dot{P}_{obs} , it is particularly sensitive to changes in our assumed model for \dot{P}_{int} , e.g. if we assume $\tau_c = 1 \text{ Gyr}$, the limit on Υ_V increases to $3 M_\odot/L_{\odot,V}$, but this result is still consistent with the smaller value reported in Table 4. In all cases, we find no evidence for an anomalously high Υ_V and our results are consistent with NGC 6517 and M22 containing no excessive amounts of low luminosity matter.

4.5. The Total Pulsar Content of NGC 6517

With the detection of four pulsars in NGC 6517 we are in a position to say something about the total pulsar content of the cluster. Pulsars are observed to follow a luminosity function of the form $dN = N_0 L^\alpha dL$. A commonly quoted value for α is -1 , though Hessels et al. (2006) find a best-fit value of $\alpha = -0.77$ among GC pulsars. Given our own data, we find best-fit values of $N_0 = 2.9$ and $\alpha = -1.32$ in NGC 6517 (model A), but given the small number of pulsars and uncertainties in the flux densities of the pulsars and distance to the cluster, we also explore models with α held fixed at -1 (model B) and -0.77 (model C). For both models B and C, the best-fit value for N_0 is about 3.0. After choosing appropriate bounds we may then integrate these luminosity functions to obtain the total number of pulsars in the cluster. We use the luminosity of the brightest pulsar as our upper bound, and choose a lower bound of 0.16 mJy kpc^2 , obtained by scaling the lowest observed GC MSP L_ν at 1.4 GHz (0.3 mJy kpc^2 ; (Hessels et al. 2007)) to 2 GHz , assuming a spectral index of -1.7 . We predict $7 f_\Omega^{-1}$ to $9 f_\Omega^{-1}$ pulsars in total, where f_Ω is the beaming fraction, depending on which model is used (see Table 5). It thus seems likely that we have discovered a large fraction of the pulsars in this cluster. However, this conclusion does depend on the assumed value of $L_{\nu,\text{min}}$. Since most pulsar searches are sensitivity limited, $L_{\nu,\text{min}}$ may be much lower than what is currently observed. To illustrate the effect of $L_{\nu,\text{min}}$ on our calculations, we also give the total number of pulsars for $L_{2 \text{ GHz},\text{min}} = 0.05 \text{ mJy kpc}^2$. This is about a factor of three lower than in the previous calculation. Model A, with its steeper power law index, is more sensitive to changes in $L_{\nu,\text{min}}$. Thus, while we cannot rule out a significant population of low-luminosity pulsars in NGC 6517, it seems likely that the total pulsar content is on the order of a dozen or so.

These numbers are consistent with what we might expect based on a simple scaling with the core interaction rate, Γ_c . For example, Terzan 5 is estimated to house ~ 60 –200 pulsars (Fruchter & Goss 2000) and has $\Gamma_c \approx 6\%$ as a fraction of the total Γ_c over all GCs. Meanwhile, based on deep Chandra observations, 47 Tucanae is estimated to house ~ 25 pulsars (independent of the radio beaming fraction) (Heinke et al. 2005) and has $\Gamma_c \approx 4\%$. Scaling down from these numbers, we would expect NGC 6517 to house about 12–17 pulsars (if we use the low estimate for Terzan 5). If Terzan 5 does indeed contain over 100 pulsars, then NGC 6517 may appear to be somewhat deficient. However, Terzan 5 has recently been shown to contain multiple stellar populations and is probably not a typical GC (Ferraro et al. 2009), so perhaps it should not be surprising that it could be an outlier. We thus find further evidence that Γ_c is a good indicator of the pulsar content in dense clusters.

Other GCs with substantial MSP populations have been observed as bright point sources by the Fermi Large Area Telescope (LAT) (Abdo et al. 2010). We followed the technique of Abdo et al. (2010) to see if NGC 6517 was visible in the LAT data. We downloaded all LAT events within a $6^\circ \times 6^\circ$ region of interest centered on NGC 6517 that accumulated between 7 August 2008 and 1 March 2011 (936 days). As is common in LAT data analysis, We only selected diffuse events and those with zenith angles $< 105^\circ$. We also applied a minimum energy cut of 200 MeV. We used the standard `P6_V3` instrument response function and the `gll_iem_v02` background model. The Fermi point source catalog was used to model known sources of emission, and we included all sources within 16° of NGC 6517, in order to properly model diffuse events that came from outside our region of interest. We then ran the `gtlike` tool, following the methods for an unbinned likelihood analysis, and the results were used to make a test statistic (TS) map of the region using `gttsmap`. The TS value around the position of NGC 6517 was only about ~ 11 , which corresponds to a significance $< 3.5\sigma$. We conclude that NGC 6517 is not yet visible as a LAT point source, probably due to its large distance. However, GCs with similar numbers of MSPs have been observed in LAT data, so it possible that NGC 6517 will be detected as the Fermi mission continues.

4.6. Non-detections in Five Clusters

We were unable to detect any pulsars in five of the clusters we searched. In light of the success of searches of clusters with relatively large values of Γ_c , it is interesting to consider what factors may have contributed to these non-detections. In all cases, it may be that any pulsars present in these clusters lie in tight binaries with accelerations beyond the range we searched. Two of the most promising clusters in our sample were NGC 6388 and Terzan 6.

NGC 6388 in particular has a higher core interaction rate than either 47 Tucanae or Terzan 5, both of which contain dozens of MSPs. NGC 6388 has also been detected as a bright Fermi point source, presumably due to the combined gamma-ray emission of an ensemble of MSPs (Abdo et al. 2010). We also believed Liller 1 was a promising target based on the Very Large Array detection of unresolved, steep-spectrum radio emission from the cluster core, which likely arises from a population of MSPs (Fruchter & Goss 2000). Recent analysis has also detected Liller 1 in Fermi data (Tam et al. 2011). We believe the most likely explanation for our non-detections in these three clusters is extensive scattering arising from inhomogeneities in the ISM. All three clusters are near the Galactic bulge and have high predicted DMs based on the NE2001 model. Following Cordes (2002), we estimate the scattering time

$$\log \tau_s = -3.59 + 0.129 \log \text{DM} + 1.02(\log \text{DM})^2 - 4.4 \log f \quad (10)$$

where τ_s is in units of microseconds, DM is in pc cm^{-3} , and f is in GHz. We find $\tau_s = 0.07, 0.25$, and 7.2 ms for NGC 6388, Terzan 6, and Liller 1, respectively, though we note that the typical scatter in the above relation is 0.65 in $\log \tau_s$. It thus seems plausible that the signal from any MSPs in these clusters was broadened beyond the point of detectability. We also observed Liller 1 at 4.8 GHz, hoping to overcome scattering by taking advantage of its steep scaling with frequency, which goes roughly as f^{-4} . These searches were also unsuccessful, probably due to a drop in pulsar flux in going to higher frequency.

M80, on the other hand, is at a higher Galactic latitude and has a modest predicted DM, making it similar in many ways to NGC 6517. Also, Tam et al. (2011) report that M80 is a possible Fermi point source. However, at $D = 10$ kpc, any pulsars in M80 may simply have fallen below our limiting flux density of $11 \mu\text{Jy}$. We note that only one MSP in NGC 6517 has flux well above this limit. We thus conclude that M80 lacks a bright MSP, but more sensitive searches could discover weaker sources. Finally, we note that NGC 6712 has the lowest Γ_c of any cluster we searched, so it is not surprising that no new MSPs were discovered.

5. Conclusion

We searched for pulsars in seven GCs with the GBT, discovering four new pulsars in NGC 6517 and two in M22. In both cases, these are the first and only pulsars found in these clusters. We were unable to identify any of the new pulsars in archival Chandra observations. The binary system NGC 6517B may be only a few hundred million years old. As this is much less than the age of the cluster, it raises the possibility of relatively recent MSP formation in NGC 6517. A second binary pulsar, M22A, is a new black widow pulsar. NGC 6517D is

an isolated MSP that lies about 20 core radii from the center of the cluster. It is difficult to explain the location of this pulsar unless it underwent a dynamical encounter that ejected it from the cluster core. We have used the observed period derivatives of three pulsars to constrain the mass-to-light ratio in these clusters, and in both cases find no evidence for significant amounts of low luminosity matter. We have also used the observed flux densities of the pulsars in NGC 6517 to estimate the total pulsar content of the cluster and find that it likely houses no more than a dozen or so pulsars, implying that we have discovered a large fraction of the population. Despite this potentially large number of MSPs, NGC 6517 was not detected in Fermi LAT data. We attribute non-detections in NGC 6388, Terzan 6, and Liller 1 to extensive scatter broadening of any pulsar signals. The discovery of MSPs in these systems will likely have to wait for observing systems that offer a significant increase in sensitivity at frequencies which are high enough to overcome scattering effects. M80 is similar to NGC 6517, but probably lacks an MSP bright enough to have been detected in our searches.

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Table 1. The Targeted High Γ_c/D^2 Globular Clusters

ID	ℓ (deg)	b (deg)	D (kpc)	DM ^a (pc cm ⁻³)	$\Gamma_c/\Gamma_{c,\text{tot}}$ ^b (%)	t_{obs} (hr)	a_{max} (m s ⁻²)	$S_{\text{nu,min}}$ (μJy)
NGC 6388	345.56	−6.74	9.9	325	8.0	1.9	15.4	38
Liller 1	354.84	−0.16	8.2	741	1.0	2.8 5.5 ^c	3.5 1.8 ^c	33 5 ^c
M80	352.67	+19.46	10.0	109	1.7	2.0	6.9	11
Terzan 6	358.57	−2.16	6.8	411	3.2	2.0	13.9	38
NGC 6517	19.23	+6.76	10.6	182.4^d	1.7	4.7	1.3	7
M22	9.89	−7.55	3.2	91.4	0.3	1.8	8.6	17
NGC 6712	25.35	−4.32	6.9	287	0.1	1.8	17.1	16

^aDM estimates for all clusters except NGC 6517 and M22 are from the NE2001 model for the Galactic distribution of free electrons (Cordes & Lazio 2002).

^b $\Gamma_c \propto \rho_0^{1.5} r_c^2$, as in the text, and $\Gamma_{c,\text{tot}}$ signifies the sum of Γ_c for all Milky Way clusters.

^cThese values are for the single 4.8 GHz search of Liller 1.

^dThe DM of NGC 6517D was not used when calculating the average DM of the cluster because it is an outlier compared to the other three pulsars.

Note. — Only clusters searched by R. S. Lynch are included. Clusters in bold face contain newly discovered pulsars. Distances, central densities, and core radii were all taken from Harris (2010). All maximum accelerations and limiting flux densities are appropriate for 3 ms pulsars with 5% duty cycles and 2 GHz searches, except the second search of Liller 1 (see note).

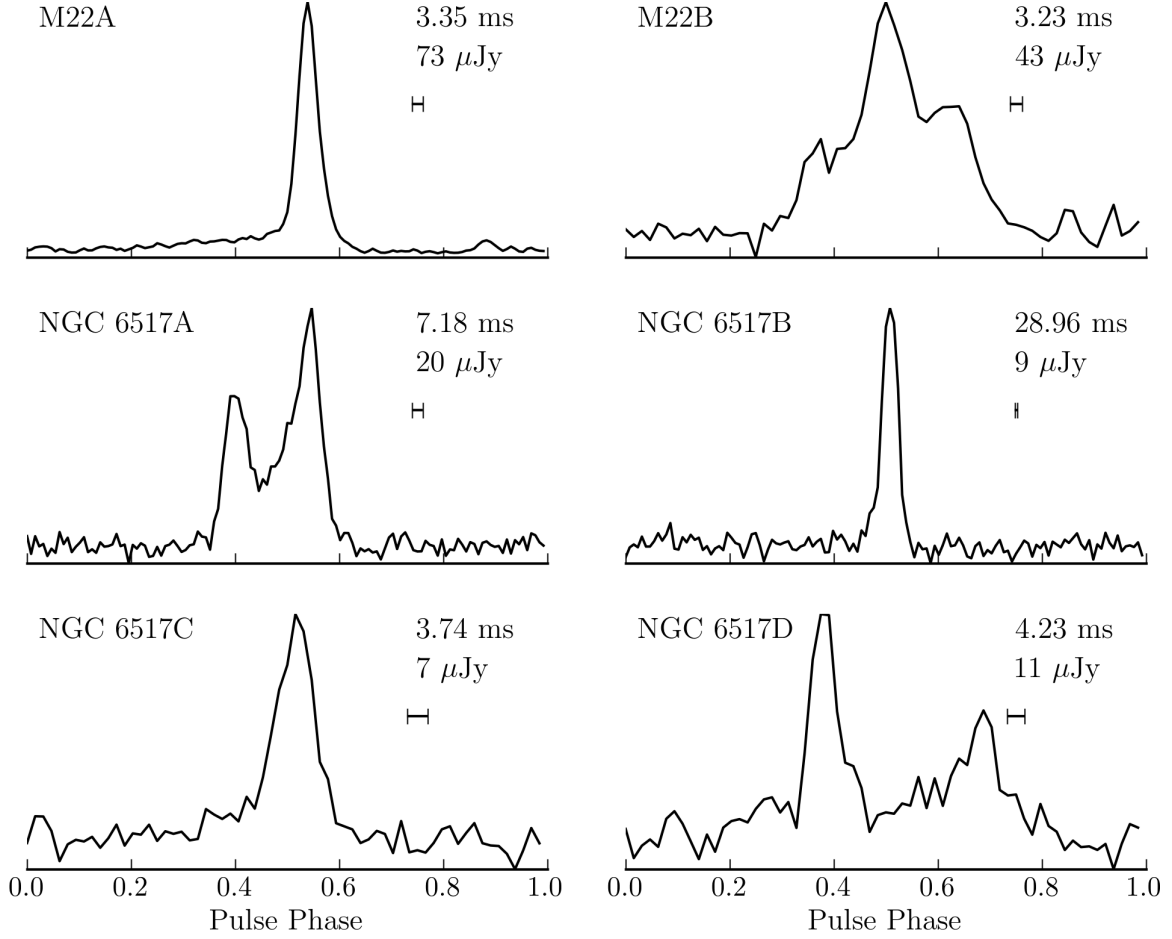


Fig. 1.— Average pulse profiles obtained by summing all detections at 2 GHz for the six newly discovered pulsars. Standard profiles for use in our timing analysis were created by fitting Gaussians to these average profiles. Pulse periods and approximate 2 GHz flux densities are also shown. The horizontal bars indicate the contribution of dispersive smearing to the pulse width.

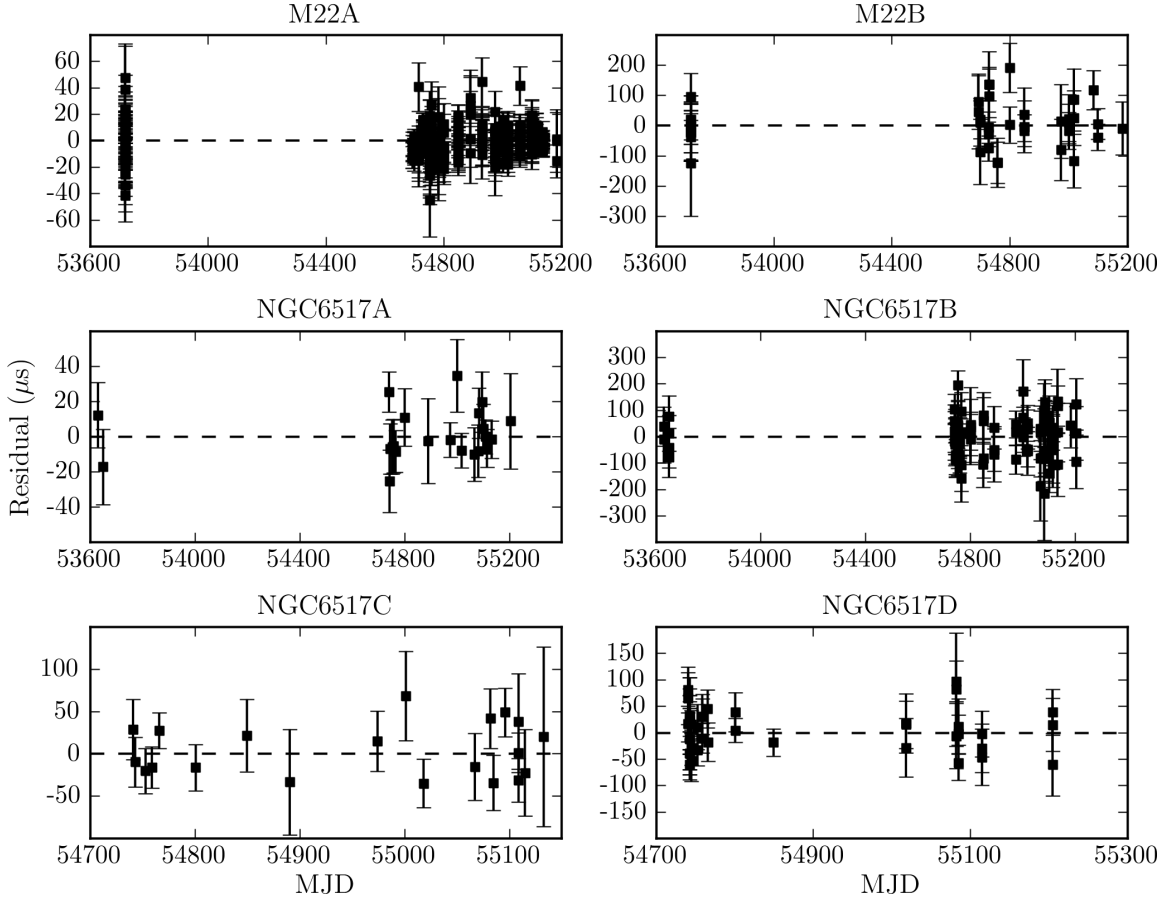


Fig. 2.— Post-fit timing residuals for each new pulsar. Only phase connected TOAs are shown. Note the different horizontal scales in each panel, particularly for NGC 6517C and D, which could not be reliably phase connected to the discovery observations.

Table 2. Isolated Pulsars

Cluster	M22		NGC 6517	
Pulsar Name	J1836-2354B	J1801-0857A	J1801-0857C	J1801-0857D
Right Ascension	18:36:24.351(3)	18:01:50.6124(2)	18:01:50.7407(7)	18:01:55.3653(5)
Declination	−23:54:28.7(7)	−08:57:31.85(1)	−08:57:32.70(3)	−08:57:24.33(3)
θ_c^a (″)	12.9	1.4	3.4	72.2
θ_c/r_c	0.2	0.4	0.9	20.1
P (ms)	3.232273969155(4)	7.1756146066706(8)	3.73869966067(2)	4.226532003547(3)
\dot{P} (s s ^{−1})	$−4.8(6) \times 10^{-22}$	$−5.1310(4) \times 10^{-19}$	$−6.5(2) \times 10^{-20}$	$6.9(6) \times 10^{-21}$
Reference Epoch (MJD)	55000	54400	54400	54400
DM (pc cm ^{−3})	93.3(2)	182.56(1)	182.26(3)	174.71(9)
RMS Residual (μ s)	64.9	11.9	28.1	36.6
N_{TOAs}	42	22	22	42
S_2 GHz (μ Jy) ^b	43	20	7	11
$S_{1.4}$ GHz (μ Jy)	40	36	12	...
Spectral index, α	0.20	−1.6	−1.5	...

^aDistance from the optical center of the cluster— $\alpha = 18:01:50.52, \delta = -08:57:31.6$ for NGC 6517 (Shawl & White 1986) and $\alpha = 18:36:23.94, \delta = -23:54:17.1$ for M22 (Goldsbury et al. 2010).

^bFlux density errors are typically ~ 10 –20%, which corresponds to an uncertainty in α of ± 1.1 .

Note. — All timing solutions use the DE405 Solar System ephemeris and UTC(NIST) clock standard. Reported uncertainties are the 1σ TEMPO errors, with the errors on the TOAs scaled such that the reduced $\chi^2 = 1$.

Table 3. Binary Pulsars

Cluster	M22	NGC 6517
Pulsar Name	J1836-2354A	J1801-0857B
Right Ascension	18:36:25.4452(1)	18:01:50.5658(5)
Declination	−23:54:52.39(3)	−08:57:32.81(3)
θ_c (″)	40.9	1.4
θ_c/r_c	0.5	0.4
P (ms)	3.3543360829062(1)	28.96158773099(3)
\dot{P} (s s ^{−1})	$2.318(3) \times 10^{-21}$	$2.1910(5) \times 10^{-18}$
Reference Epoch (MJD)	55000	54400
DM (pc cm ^{−3})	89.107(2)	182.39(6)
P_b (d)	0.2028278011(3)	59.8364526(6)
$a \sin i/c$ (lt-s)	0.0464121(6)	33.87545(2)
T_0 (MJD)	54694.1962891(6)	54757.7226(2)
e	$< 2.8 \times 10^{-4}$	0.0382271(7)
ω (deg)	...	302.106(1)
Mass Function (M_\odot)	$2.6091(1) \times 10^{-6}$	0.01165753(2)
$M_{c,\min}^a$ (M_\odot)	0.017	0.33
RMS Residual (μ s)	7.3	71.2
N_{TOAs}	355	83
$S_{2\text{ GHz}}$ (μ Jy)	73	9
$S_{1.4\text{ GHz}}$ (μ Jy) ^b	200	12
Spectral index, α	−2.8	−0.81

^aWe assume a pulsar mass of 1.4 M_\odot .

^bFlux density errors are typically ~ 10 –20%, which corresponds to an uncertainty in α of ± 1.1 .

Note. — All timing solutions use the DE405 Solar System ephemeris and UTC(NIST) clock standard. Reported uncertainties are the 1σ TEMPO errors, with the errors on the TOAs scaled such that the reduced $\chi^2 = 1$.

Table 4. Constraints on Mass-To-Light Ratio

Pulsar	\dot{P}_{obs}	\dot{P}_{int}	\dot{P}_{Gal}	\dot{P}_{pm}	\dot{P}_{cluster}	$\sigma_{\text{M}}^{\text{a}}$ ($10^5 \text{ M}_{\odot} \text{ pc}^{-2}$)	Υ_{V} Lower Limit ($\text{M}_{\odot}/\text{L}_{\odot,\text{V}}$)
			($10^{-20} \text{ s s}^{-1}$)				
NGC 6517A	−51	1.2	−1.1	...	−51	14	2.3
NGC 6517C	−6.5	0.59	−0.60	...	−6.5	3.4	0.55
M22B	−0.05	0.51	0.14	0.25	−0.95	0.57	0.51

^aMass surface density

Table 5. Total Number of Pulsars in NGC 6517

Model ID	N_0	α	$N_{\text{psr}} f_{\Omega}^{-1}$ Given $L_{2 \text{ GHz}, \text{min}}$ 0.16 mJy kpc ²	0.05 mJy kpc ²
A	2.9	−1.32	9	17
B	3.0	−1.0	8	12
C	3.0	−0.77	7	9

Note. — For a luminosity function of the form $dN = N_0 L^{\alpha} dL$. Models are defined in the text.